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**Application of Coupled Optoelectronic Oscillator on Optical  
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**Abstract**

A coupled optoelectronic oscillator (COEO) with a polarization-maintaining-fiber based laser cavity is constructed and demonstrated. The mode-locking process and the interaction between the intra cavity power and dispersion is investigated to stabilize and optimize the system. This standalone signal source is capable of outputting pure 10.1 GHz RF signal as well as stable ultrashort optical pulses at corresponding repetition rate simultaneously. The phase noise of the 10.1 GHz RF signal is measured to be as low as -133.25 dBc/Hz at 10 kHz offset frequency. With its dual output of self-synchronized high-quality RF carrier and optical pulses, such a signal generator could be applied as the pulse and clock source in a high speed photonic assisted sampling analog-to-digital converter (ADC) and improve the system performance.

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**Keywords:** Coupled optoelectronic oscillator; microwave photonics; signal generation

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**1. Introduction**

Optoelectronic oscillator (OEO) is a new kind of phonic microwave signal generator which can turn continuous laser waves into high-quality and high-frequency microwave signals with extreme spectral purity and ultra-low

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phase noise [1]. Oscillators produce signals that regulate the data generation, transmission, and processing by setting the clock speed or acting as the data carriers in any data systems. With its high frequency and low phase noise features, OEO is very welcomed in modern high data rate system or high performance radar systems. One distinguished advantage of OEO is that, it has the ability of generating tens of gigahertz microwave signals with great flexibility, only limited by the bandwidths of the electrical or optoelectronic devices.

The coupled optoelectronic oscillator (COEO) can simultaneously generate short optical pulses and spectrally pure radio frequency (RF) signals [2]. It can be considered as a combination of a traditional general single loop OEO and a regenerative harmonically mode-locked fiber laser (MLFL) [3]. As comparing to the OEO, the COEO employs an extra optical fiber laser loop to serve as an equivalent active optoelectronic filter to largely enhance the Q factor, improve the sidemode suppression and provide an additional optical pulses output. While comparing to a regenerative harmonically MLFL, the COEO utilizes an extra optoelectronic feedback loop for the RF signal generation so as to eliminate the external RF synthesizer. Therefore COEO is a promising stand-alone compact source for both millimeter wave signals and sub-picoseconds optical pulses.

We have proposed a COEO which consists of a polarization maintaining fiber based laser cavity. With all the fiber connections inside the laser are polarization-maintaining type, we no longer need extra polarization controller or polarization beam splitter for polarization optimization [2, 4]. To achieved best mode locking state and for easier system reconfigurability, a miniature motorized optical variable delay module (OVDL) is used to control the laser cavity length and a tunable optical bandpass filter (TOBPF) is used to adjust the lasing wavelength thus controlling the effective total cavity dispersion. For the optimization of the phase noise performance, laser pump power and lasing wavelength are tuned to affect the cavity linearity and dispersion. With only a laser cavity length of 120m, the achieved best phase noise is -133.25 dBc/Hz at 10 kHz offset for the 10.1 GHz carrier. Stable pulses at 99 ps repetition rate and with 20 ps pulse width have been generated simultaneously with an integration timing jitter from 100 Hz to 10 MHz as low as 55.9 ps. Such a compact signal source can be conveniently applied as the pulse and clock source in a photonic analog-to-digital converter (ADC) system.

## 2. Experimental results and discussion

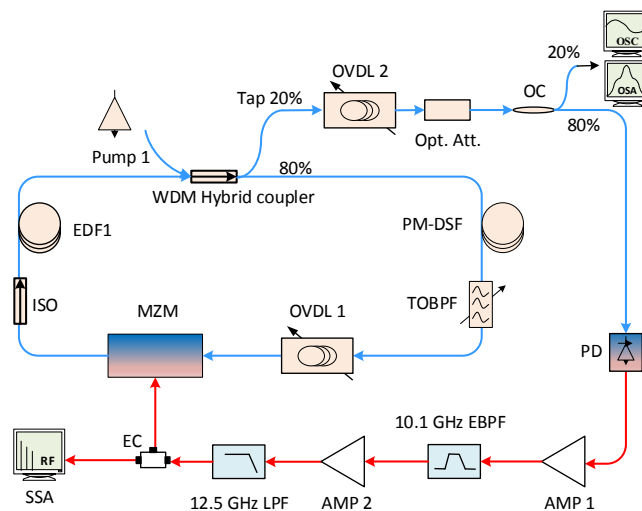


Fig. 1. Experimental setup of the proposed coupled COEO.

The experiment setup is shown as in Fig.1. The gain medium is polarization maintaining Erbium-doped fiber (PM-EDF). The optical isolators (ISOs) before and after the EDF are for unidirectional operation. The later ISO is integrated with a wavelength division multiplexing (WDM) hybrid coupler. 980 nm pump is injected through this coupler, which is also integrated with a 20% tap. The 80% output of the WDM coupler is transmitted through a 100

meters long polarization maintaining dispersion shifted fiber (PM-DSF), and then filtered by a tunable optical bandpass filter (TOBPF). This 5 nm TOBPF is not only for pulse width control, it also helps the lasing wavelength tuning. The miniature motorized optical variable delay module (OVDL1) is for cavity length adjustment to ensure stable mode-locking. Especially when the electrical bandpass filter (EBPF) in the RF feedback link is changed, the OVDL1 will help quickly make the COEO system relocked. The LiNbO<sub>3</sub> Mach-Zehnder modulator (MZM) is for the RF injection for mode-locking and RF feedback. The 20% tap out of the WDM coupler is transmitted through the other miniature motorized optical variable delay module (OVDL2), which is used to tune the feedback phase. The optical tunable attenuator is to protect the photodetector as well as help control the open-loop gain. The 20/80 coupler is to extract 20% of the optical signal as the optical output and the 80% injected to the photodetector (PD) for OEO feedback. The recovered RF signal is amplified by a low phase noise amplifier (AMP1), filtered by a 10.1 GHz narrowband electrical bandpass filter (EBPF) and re-amplified by AMP2. AMP1 and AMP2 are the same model and have a gain of 20dB. The 12.5 GHz low pass filter (LPF) is used for eliminating harmonics generated by the amplifiers. The electrical output is from the 10 dB electrical coupler and observed by a signal source analyser (SSA). Meanwhile, the optical output is observed from the optical 20% optical coupler by an optical spectrum analyser (OSA) and a sampling oscilloscope (OSC).

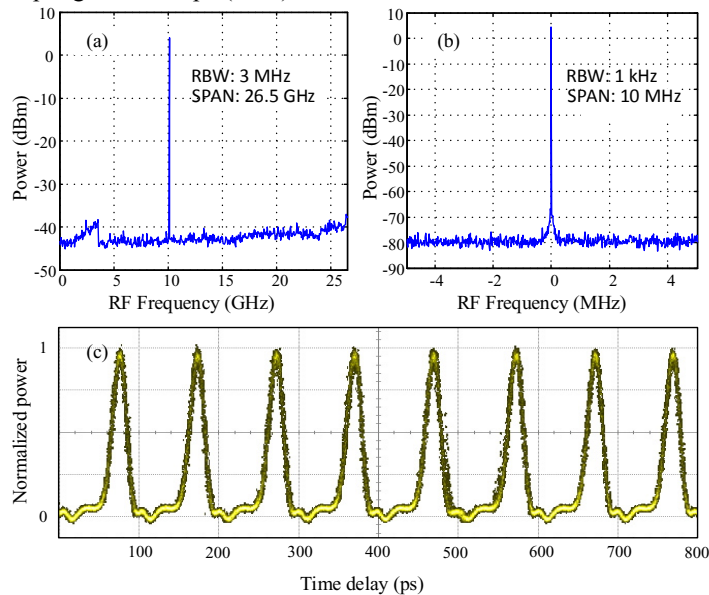


Fig. 2. RF spectral of the generated 10.1 GHz. (a) In 26.5 GHz span; (b) in 10 MHz span.

Fig. 2 (a) and (b) show the RF spectrum of the generated 10.1 GHz signal in 26.5 GHz span and in 10 MHz span respectively. From Fig.2 (a), it can be seen that the COEO can generate a single frequency of 10.1 GHz without any harmonics. From Fig.2 (b), it shows that the COEO is in well mode-locked state with all the cavity modes have been suppressed by more than 80 dB. For the proposed COEO, the cavity mode is 1.7 MHz which is determined by the 120 meters long cavity. Fig. 2 (c) shows the optical pulses directly captured by the optical sampling oscilloscope. The pulse repetition rate is 99 ps and the pulse width is about 20 ps. The timing jitter calculated by integrating the phase noise spectral density from 100 Hz to 10 MHz offset frequencies is as low as 55.9 fs. The proposed COEO is successful in simultaneously generated RF signal and stable optical pulses.

The phase noise of this signal has been measured as well which is shown in Fig. 3. For our SSA, the cross-correlation phase noise measuring module is only up to 8 GHz, so we have to use a frequency divider to down-converted the 10.1 GHz to 5.05 GHz first, measure the phase noise of the 5.05 GHz signal and then plus 6 dB to obtain the phase noise of the original 10.1 GHz signal. The acquired value at 10 kHz offset for 10.1 carrier is as low

as -133.25 dBc/Hz, which is good regarding to our cavity length. It is anticipated that after packaging the system and thermally isolate it, the noise performance could be further improved.

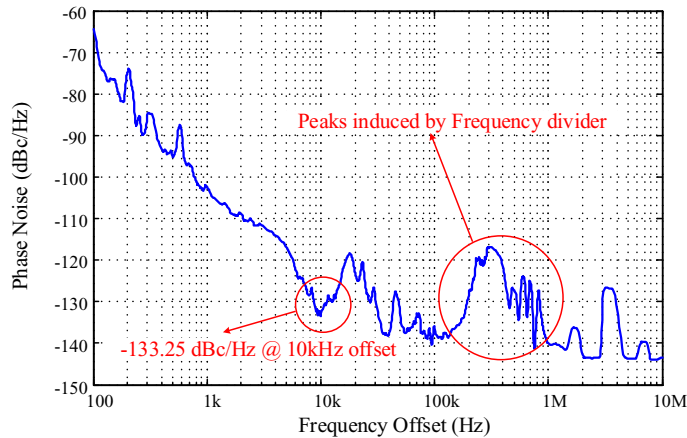


Fig. 3. The phase noise of the generated 10.1 GHz RF signal

The pulse duration and pulse chirp are key factors in determine the phase noise of the COEO RF output [5]. Since we haven't got any polarization type dispersion compensating device yet, we tune in our system is the TOBPF and the pump power to optimize the phase noise result. By tuning the TOBPF the pulse wavelength could be changed thus the equivalent dispersion. By altering the pump the nonlinearity within the cavity could be changed. Fig. 4 shows the phase noise value at 10 kHz offset varies along with the tuning of the pump driving current and it reaches the optimal value at around 450 mA, namely at 22.56 dBm pump power for the fiber laser.

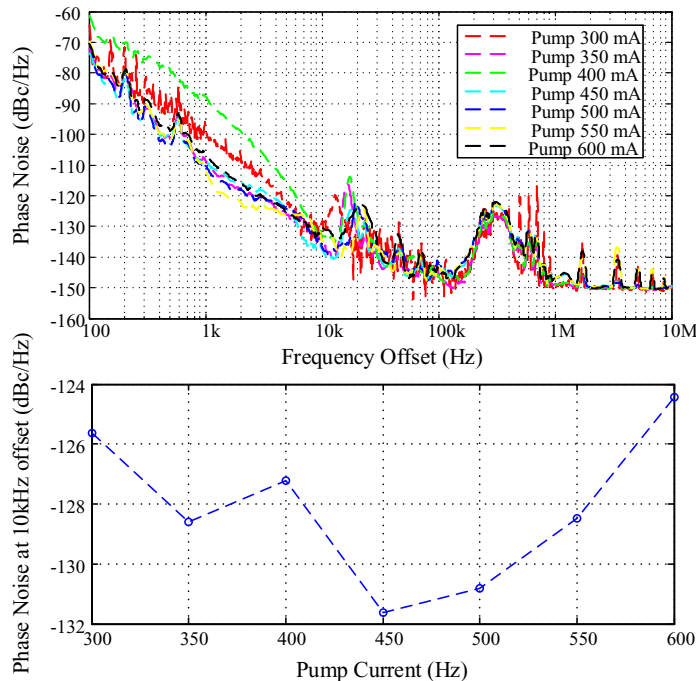


Fig. 4. Phase noise optimization by adjusting the pump. (a) Phase noise plots under different pump driving current; (b) Phase noise value at 10 kHz offset corresponding to the curves in (a).

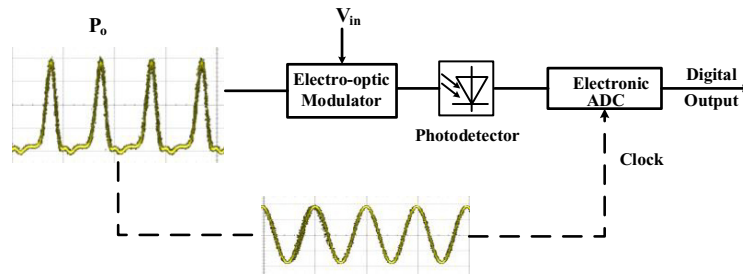


Fig. 5. Application illustration of the COEO in a photonic assisted sampling ADC system.

COEO can generate pure RF signal and stable optical pulses simultaneously, it is very convenient to combine it with a photonic ADC as illustrated in Fig. 5. Since the EBPF in present COEO is centered at 10.1 GHz which is not suitable for the electronic ADC so the application hasn't been implemented yet. Some of our group members have utilized a 2 GHz regeneratively mode locked laser in a photonic ADC system as the pulse source [6, 7]. Our COEO has similar structure but focus more on the phase noise improvement by inserting long fiber in the laser cavity. The system could be easily reconfigured by replace the EBPF with different center frequency and adjusted by the OVDL and TOBPF to new stable mode-locked state. So similar applications with improved performance can be realized with our present COEO.

### 3. Conclusion

A simplified COEO based on all polarization maintain fiber and devices is constructed and demonstrated. It can generate pure RF signal at 10.1 GHz with the phase noise as low as -133.25 dBc/Hz with only 120 m cavity length. The timing jitter of the generate pulse is 55.9 ps integrated from 100 Hz to 10 MHz. The OVDL and TOBPF inside the laser cavity bring the COEO with easy reconfigurability, making it an excellent compact pulse and clock source for a photonic assisted sampling ADC system.

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